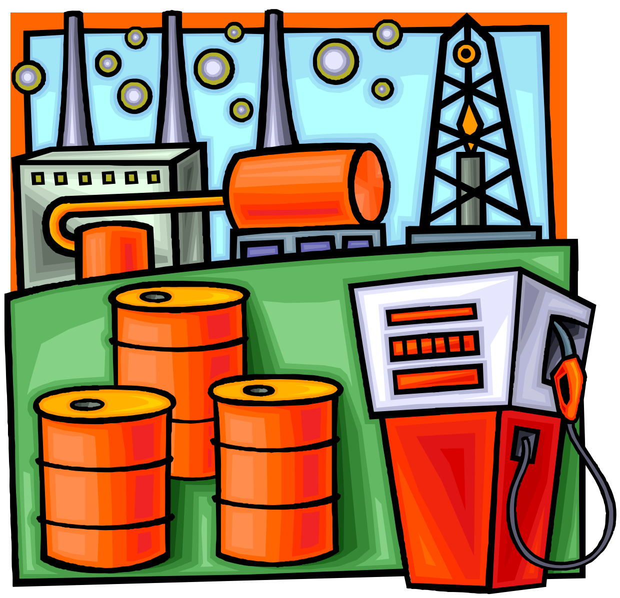
California Environmental Protection Agency

Air Resources Board

Detailed CA-GREET Pathway for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) from Average Crude Refined in California



Stationary Source Division

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(The ARB acknowledges contributions from the Energy Commission, TIAX and Life Cycle Associates during the development of this document)

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These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

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SUMMARY

CA-GREET Model Pathway for CARBOB from Average Crude Refined In California

Well-To-Tank (WTT) Life Cycle Analysis of a petroleum based fuel pathway includes all steps from crude oil recovery to final finished fuel. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. WTT and TTW analysis are combined to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)[1] developed by Argonne National Laboratory and modified by TIAX during the AB 1007 process[2] was used to calculate the energy use and greenhouse gas (GHG) emissions generated during the process of transforming crude to produce California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB)[3]. Using this model, staff developed a pathway document for CARBOB which was made available in mid-2008 on the Low Carbon Fuel Standard (LCFS) website (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model[4]. This updated California modified GREET model (version 1.8b) (released February 2009) forms the basis of this document. It has been used to calculate the energy use and greenhouse gas (GHG) emissions associated with the production and use of CARBOB.

The pathway includes crude recovery, transport, refining of crude in a typical California refinery and transport of finished product (CARBOB). For the CARBOB pathway, the TTW does not truly include combustion since CARBOB can not be used as a fuel per regulations established by the Air Resources Board. A similar analysis of an oxygenate such as ethanol is necessary to allow for combining the necessary energy and GHG contributions to provide for a total WTW analysis of California Reformulated Gasoline (CaRFG), a mixture of ethanol (3.5 wt.% oxygen) in CARBOB. ARB staff has developed a similar analysis for ethanol which is combined with this analysis to provide a WTW analysis for CaRFG, also available on the LCFS website. Figure 1 show below details the discrete components that form the CARBOB pathway, from crude recovery through final finished fuel blending component. Utilizing the energy and GHG emissions from each component, a total for the entire CARBOB pathway is then calculated.

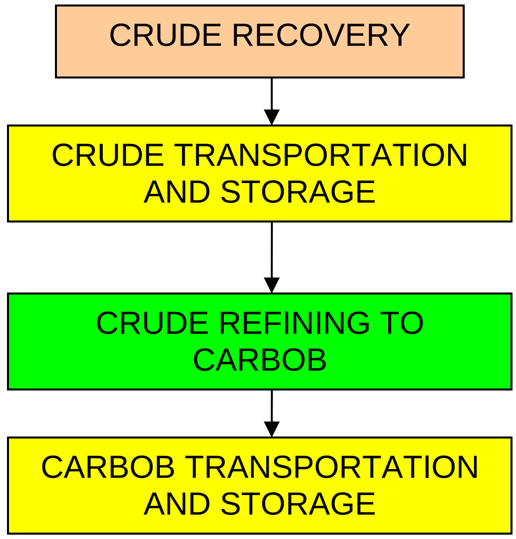


Figure 1. Discrete Components of Crude to CARBOB Pathway

This document provides detailed calculations, assumptions, input values and other information required to calculate the energy use and GHG emissions for the CARBOB pathway. Although the original GREET model developed by Argonne National Laboratory forms the core basis of this analysis, it has been appropriately modified to reflect California specific conditions. Examples include electricity generation factors, crude transportation distances, etc. which have been used to replace to the original GREET input values. A detailed list of all input values is provided in Appendix B.

Table A provides a summary of the Well-To-Tank (WTT) and Tank-To-Wheel (TTW) energy use and GHG emissions for this pathway. Energy use is presented as Btu/mmBtu and GHG emissions are reported as g CO_2e/MJ, where non-CO_2 gasses (i.e., methane and nitrous oxide) are converted into CO_2 equivalents. Details of converting non-CO_2 gasses to CO_2 equivalents are detailed in Appendix A in this document.

Note: The energy inputs are presented in mmBtu because the calculations in the CA-GREET model use mmBtu.

Table A. Summary Energy and GHG Values for the CARBOB Pathway

	Energy Required (Btu/mmBtu)	% Energy Contribution	Emissions (gCO_2e/MJ)	% Emissions Contribution
Crude Recovery	80,345	6.14%	6.93	7.29%
Crude Transport	16,265	1.24%	1.14	1.20%
Crude Refining (CA)	206,372	15.77%	13.72	14.43%
CARBOB Transport	5,632	0.43%	0.36	0.38%
Total (Well To Tank)	**308,614**	**23.58%**	**22.04**	**23.19%**
Total (Tank To Wheel)	**1,000,000**	**76.42%**	**72.91**	**76.81%**
Total (Well To Wheel)	**1,308,614**	**100%**	**95.06***	**100%**

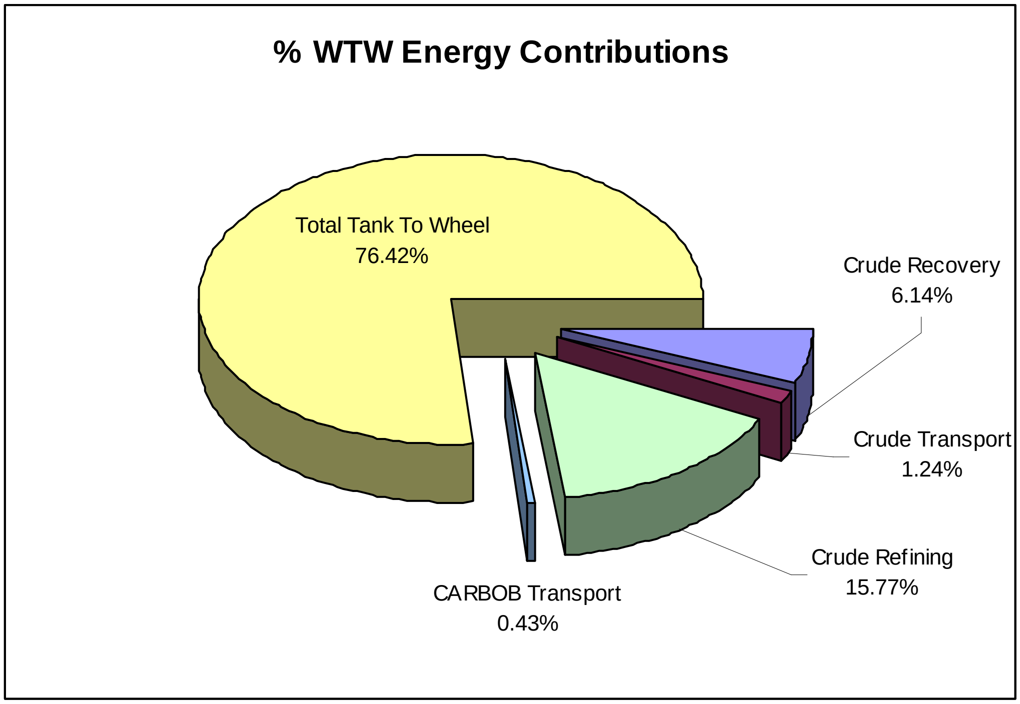
Note: percentages may not add to 100 due to rounding

***Allocating tailpipe emission factors to CARBOB when used in CaRFG leads to a total of WTW emissions for CARBOB of 95.86 gCO_2e/MJ. Please refer to CaRFG document for details of this calculation.**

From Table A above, the WTW analysis of CARBOB indicates that **1,308,614** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy delivered to the vehicle. From a GHG perspective, **95.06** gCO_2e of GHGs are released during the production of 1 (one) MJ of CARBOB. Note that this analysis uses average crude recovery which takes into consideration crude extracted in California as well as crude recovered overseas. The transportation of crude via ocean tanker from overseas locations and pipeline from Alaska is also weighted to reflect average crude available in California.

Note that WTW values calculated in Table A do not represent a true WTW since CARBOB is prohibited from being used as a fuel in a motor vehicle. Only the carbon in fuel which is transformed into CO_2 is included in the WTW analysis in this document and the calculations are provided in Appendix A. A complete WTW analysis would include not only the CO_2 generated from carbon in the fuel but would also account for N_2O and CH_4. Using a similar analysis for ethanol (used as an oxygenate), staff has provided details of a WTW analysis for CARBOB blended with ethanol fuel to make CaRFG (California Reformulated Gasoline). When tailpipe emission factors are included in the CARBOB pathway, WTW emissions are calculated to be **95.86 gCO_2e/MJ** details of which are included in the CaRFG pathway document.

The values in Table A are illustrated in Figure 2, showing specific contributions of each of the discrete components of the fuel pathway. The charts are shown separately for energy use and GHG emissions. From an energy use viewpoint, energy in fuel (76.42%) and crude refining (15.77%) components dominate the WTW energy use. From a GHG perspective, carbon in fuel (76.81%), crude refining (14.43%), and crude recovery (7.29%) components dominate the GHG emissions for this pathway.



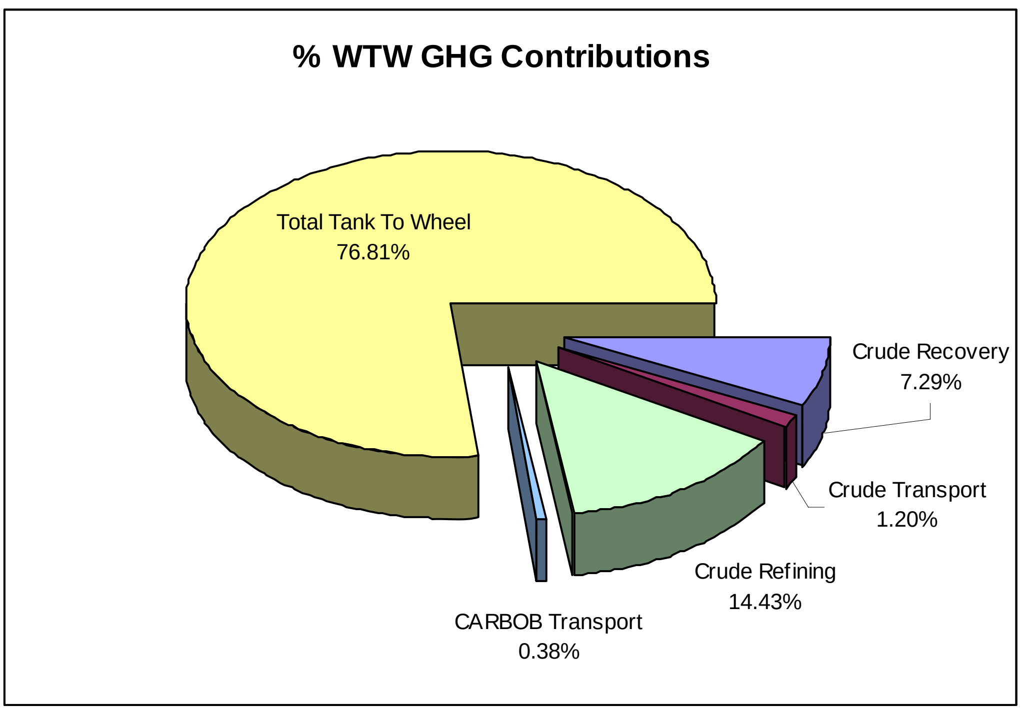


Figure 2. Percent Energy Contributions and Emissions Contributions for the CARBOB Pathway

WTT Details-Crude Recovery

Table B provides a breakdown of energy use for crude recovery. Crude recovery utilizes process energy which CA-GREET depicts as being derived from a combination of several fuel types including crude itself, residual oil, diesel, gasoline, natural gas and electricity. As an example, natural gas used as a fuel is combusted in a boiler to generate heat which then runs a turbine to generate electricity. This feature is captured in the electricity fuel share part of the energy mix. The table indicates that **80,345** Btu of energy is required, on average, to recover crude containing 1 mmBtu of energy. Detailed calculations are provided in Appendix A.

Table B. Total Energy use for Crude Recovery

Fuel Type	Btu/mmBtu
Crude oil	134
Residual oil	145
Diesel fuel	2,278
Gasoline	314
Natural gas	75,558
Coke (Pet. Coke)	1,840
Feed Loss	75
Total energy for crude recovery	**80,345**

In a similar manner, GHG emissions associated with the transformation of fuel sources to useful process energy for crude recovery are shown in Table C below. Additional details are provided in Appendix A. GHG emissions from all crude supplied to CA refineries produces **6.93** gCO_2e/MJ of GHG emissions.

Table C. Total GHG Emissions from Crude Recovery

	gCO_2e/MJ
CO_2	5.27
CH_4	2.09
N_2O	0.03
CO	0.03
VOC	0.01
Total GHG emissions	**6.93**

WTT Details-Crude Transport and Storage

Table D shows the energy necessary for transporting crude via ocean tanker and pipeline to California refineries. The proportional split between these two modes of transport is calculated from the average crude mix arriving in California, both from within the state as well as from overseas. Detailed breakdown of proportions utilized in the calculations are provided in Appendix A. A small energy loss attributable to feed losses is also captured in this analysis. As shown in the Table below, crude transport utilizes an average of **16,265** Btu of energy for every 1 mmBtu of crude transported.

Table D. Energy Consumed for Crude Transport

	Btu/mmBtu
Feed Loss	62
Ocean Tanker	7,104
Pipeline	9,073
Barge	88
Total Crude Recovery	**16,265**

Table E captures GHG emissions from crude transport in ocean tankers and pipelines. The fuel consumption and other specifics necessary for this calculation are detailed in the Appendix A. Crude transport by the two types of transport weighted proportionally generates **1.14** gCO_2e GHG emissions for every 1 MJ of crude transported.

Table E. Total GHG Emissions Crude Transport and Distribution

GHG	**g CO_2e/MJ**
CO_2	1.07
CH_4	0.04
N_2O	0.01
CO	0.00
VOC	0.00
Total GHG emissions	**1.14**

WTT Details-Crude Refining

Table F provides energy source mix used in refining of California average crude mix to CARBOB. This is similar to the energy mix analysis presented in crude recovery earlier. As can be seen in the Table below, **206,372** Btu of energy is required to produce 1 mmBtu of finished CARBOB. Again here, each source of fuel has associated GHG emissions in its transformation into useful energy and these are shown in Table G below. The refining process generates **13.72** grams of CO_2e per MJ of finished fuel. Details of all the calculations are presented in Appendix A.

Table F. Energy Required for Crude Refining to CARBOB

Fuel Type	Btu/mmBtu
Residual Oil	6,421
Natural Gas	58,841
Pet. Coke	24,321
Electricity	16,682
Refinery still gas	100,107
Total energy for refining	**206,372**

Table G. GHG Emissions from Crude Refining to CARBOB

GHG	g CO_2e/MJ
CO_2	11.94
CH_4 (combustion)	0.30
N_2O	0.04
CO	0.01
VOC	0.00
VOC, CO and CO_2 from non-combustion sources	1.40
Total	**13.72**

WTT Details-CARBOB Transport and Storage

Table H provides a summary of the energy used to transport finished CARBOB via pipeline and Heavy Duty Diesel (HDD) truck from refineries to a blending station. From Table H, this component of the pathway utilizes **5,632** Btu of energy for every 1 mmBtu of CARBOB transported. The transportation through pipeline and HDD truck generates GHG emissions which are shown in Table I below. A total of **0.36** gCO_2e GHG emissions are generated for every 1 MJ of CARBOB transported.

Table H. Energy Use for CARBOB Transportation and Distribution

Transport mode	Btu/mmBtu
Feed Loss	813
CARBOB transported by pipeline	642
CARBOB Transport by HDD truck	699
CARBOB Distribution by HDD truck	3477
Total	**5,632**

Table I. GHG Emissions from Transporting and Distributing CARBOB

GHGs	Total (gCO2e/MJ)
CO_2	0.34
CH_4 (converted to CO_2e)	<0.01
N_2O (converted to CO_2e)	<0.01
CO (converted to CO_2)	<0.01
VOC (converted to CO_2)	<0.01
Total GHGs	**0.36**

<u>TTW Details-CARBOB Carbon in Fuel</u>

Since CARBOB can not be used as a fuel per Air Resources Board regulations (no oxygenate in CARBOB), actual TTW calculations can not be made for CARBOB to account for CO_2, CH_4, CO, N_2O and VOC emissions. Table J below provides a summary of the carbon in fuel calculations, details of which are provided in Appendix A. The carbon content of CARBOB generates **72.91** gCO_2e/MJ, which in effect represents perfect combustion of the carbon in CARBOB to CO_2 and water.

Table J. Carbon in Fuel Calculations for CARBOB

CO_2 from fuel = Density * carbon ratio in gasoline/(C factor * Lower Heating Value) = **72.91** g CO_2/MJ

APPENDIX A

Section 1. CRUDE RECOVERY

1.1 Energy Use for Crude Recovery

California crude is derived from various countries. Table 1.01 provides a breakdown of the sources for California. The data was obtained from the California Energy Commission website[5]. This document utilized the 2006 supply to calculate the appropriate weightings for crude recovery and crude transport.

Table 1.01. Crude Oil Sources for California Refineries (barrels/year)

Feedstock Location	2005 CEC	2006 CEC	2007 CEC
Alaska, Valdez	135,906,000	105,684,000	100,900,000
Saudi Arabia	95,507,000	86,976,000	72,296,000
Ecuador	67,705,000	71,174,000	55,456,000
Iraq	34,160,000	56,163,000	57,788,000
Brazil	12,474,000	17,938,000	22,453,000
Mexico	19,316,000	15,473,000	9,214,000
Angola	12,912,000	14,979,000	21,038,000
Columbia	4,180,000	9,362,000	11,813,000
Oman	2,985,000	6,326,000	
Venezuela		4,120,000	4,706,000
Argentina	6,213,000	3,484,000	
Nigeria			5,447,000
Others	13,707,000	9,311,000	21,313,000
Canada	4,942,000		5,320,000
California	266,052,000	254,498,000	251,445,000
Total	**676,059,000**	**655,488,000**	**639,189,000**

Sources: California Energy Commission

Energy requirements in CA-GREET for crude recovery utilize a recovery efficiency which is used to calculate energy needs for this process. The default value in GREET is 98%, which reflects an average of crudes processed in the U.S. The crude recovery efficiency (93.0%) used here however, is a weighted average and takes into consideration crude extracted in California, crude transported from Alaska as well as worldwide crude that is imported into California. The 93.0% value represents an estimate of a mix of conventional oil recovery and *Thermally Enhanced Oil Recovery* (TEOR). Approximately 38.9% of total crude for CA in produced in the state and 38.3% of CA crude is produced using TEOR methods, which use steam injection to recover heavier oil products. Since TEOR requires steam to be injected into the oil reserves, the process uses more energy than conventional oil recovery. Some TEOR sites also co-generate electricity, which is used to provide power for the oil recovery operations, other oil recovery sites, and export to the grid. According to California Department of Conservation, in California, 95% of the power generation capacity for TEOR sites is natural gas derived with the balance coal fired[6].

Of the 38.3% crude produced using TEOR, 40% is produced with co-generated electricity. An electricity credit is calculated for electricity exported to the grid based on CEC data for TEOR cogeneration projects. The co-product electricity generated is 0.0041 Btu electricity/Btu crude produced and is calculated outside of CA-GREET based on CA crude data. The credit is based on the net electricity export after the input electricity has been subtracted.

Table 1.02 shows details of the types and proportion of various fuels used in crude recovery. The values in Table 1.02 are adjusted to account for the WTT energy used to produce each fuel. Table 1.03 depicts the adjustments to the values from the table above for each fuel type, accounting for loss factors associated with the WTT energy for each fuel used during crude recovery operations. Table 1.04 provides values and descriptions for the equations used in Table 1.03.

Table 1.02. Details on How Efficiency is Used to Calculate Energy Consumption for Crude Recovery

Fuel Type	**Fuel Shares**	**Relationship of Recovery Efficiency (0.93) and Fuel Shares**	**Direct Energy (Btu/mmBtu)**
Crude oil	0.2%	$(10^6)(1/0.93 - 1)(0.002) = 124$	124
Residual oil	0.2%	$(10^6)(1/0.93 - 1)\ (0.002) = 124$	124
Diesel fuel	2.5%	$(10^6)(1/0.93 - 1)\ (0.086) = 1{,}867$	1,867
Gasoline	0.3%	$(10^6)(1/0.93 - 1)(0.011) = 249$	249
Natural gas	94.3%	$(10^6)(1/0.93 - 1)(0.943) = 70{,}595$	70,595
Coal and Pet. Coke	2.4%	$(10^6)(1/0.93 - 1)(0.0024) = 1{,}803$	1,803
Electricity	0%	$(10^6)(1/0.93 - 1)(0) = 0$	0
Feed Loss	0.1%	$(10^6)(1/0.93 - 1)(0.001) = 75$	75
Natural Gas Flared		Weighted average for worldwide crude for CA refineries	13,107

*Additional 4,314 Btu/mmBtu credit for electricity co-produced is applied to average petroleum.

Table 1.03. Adjustment to Crude Recovery Energy to Account for Losses and WTT Energy Inputs

Fuel Type	Formula	Btu/mmBtu
Crude oil	$124 (1 + A/10^6)$	134
Residual oil	$124 (1 + (B*D+ C)/ 10^6)$	145
Diesel fuel	$1867 (1 + (B*F + E)/ 10^6)$	2,278
Gasoline	$249 (1 + (B*H + G)/ 10^6)$	314
Natural gas	$70{,}595 (1 + I/10^6)$	75,558
Coke (Pet. Coke)	$1{,}803 (1+J/10^6)$	1,840
Electricity	$0 (K + L)/ 10^6$	0
Feed Loss	75	75
Total WTT energy for crude recovery		**80,345**

Table 1.04. Details for Formulas in Table 1.03

Quantity	Description
A = 80,345	WTT energy in Btu for crude recovery at the oil field. This value calculated as the total WTT energy for crude recovery in Table 1.02 above. It is also an input the total WTT energy calculation This is one instance of a “recursive” calculation in CA-GREET.
B = 91,815	WTT energy of crude in Btu consumed to recover one million Btu as feedstock used in US refineries. This is a CA-GREET calculation that includes losses and delivery to the oil refinery.
C = 77,138	WTT energy in Btu required to produce 1 million Btu of residual oil. This is calculated from the WTT analysis of residual oil similar to the CARBOB calculations being detailed in this document.
D = 1.0000	Loss factor for Residual Oil which is a CA-GREET default value.
E = 128,548	WTT energy required in Btu to produce one million Btu of diesel. This value is calculated from the WTT analysis of diesel from CA-GREET similar to the CARBOB calculations being detailed in this document.
F = 1.0000	Loss factor[1] for diesel fuel which is default CA-GREET value.
G = 169,132	WTT energy in Btu to produce one million Btu of gasoline. This value is calculated from the WTT analysis of gasoline from CA-GREET similar to the CARBOB calculations being detailed in this document.
H = 1.00008	Loss factor[1] for gasoline which is default CA-GREET value.
I = 70,299	WTT energy in Btu used to produce natural gas as stationary fuel. This is a CA-GREET calculated value.
J = 20,961	WTT energy in Btu used to produce coal as stationary fuel. This is a CA-GREET calculated value.
K = 2,793,243	Total energy required in Btu to produce one million Btu of electricity. This is derived from the electricity analysis by CA-GREET.
L = 192,311	Total energy required Btu to produce one million Btu of electricity feedstock. This is derived from the electricity analysis by CA-GREET.

[1]Loss factors for petroleum fuels include refueling spillage plus evaporative losses from vehicle fueling and fuel transfer operations.

1.2 GHG Emissions from Crude Recovery

For all greenhouse gas (GHG) emissions, CA-GREET accounts for only three GHGs: CO_2, CH_4 and N_2O. For CO and VOCs, the model calculates the CO_2 when these components are oxidized in the atmosphere. The Global Warming Potentials (GWP) for all gases are default CA-GREET values and listed in Table 1.05. Information on VOC and CO conversion calculations is provided as a note below.

Table 1.05. Global Warming Potentials for Gases (CA-GREET Default per IPCC[7])

Species	GWP (relative to CO_2)
CO_2	1
CH_4	25
N_2O	298

Note: values from mmBtu to MJ have been calculated using 1 mmBtu = (1/1055) MJ
Carbon ratio of VOC = 0.85which is converted to gCO_2e/MJ = grams VOC*(0.85 gC/gVOC)*(44 gCO_2/12 g C).
Carbon ratio of CO = 0.43 which is converted to gCO2e/MJ = grams CO*(0.43 gC/gCO)*(44 gCO_2/12 g C)

The transformation of various fuel types into energy generates emissions, specific to each type of fuel and the equipment used in the transformation. An example is natural gas being combusted to generate electricity in turbines. Table 1.06 details only CO_2 emissions for each fuel type used in crude recovery. CH_4, N_2O, VOC and CO contributions to total GHG emissions are detailed later in this section. Additional details for each specific fuel type are provided in sections to follow. The table provides GHG values both in g CO_2/mmBtu and g CO_2/MJ. As an example, the use of diesel fuel in crude recovery generates 0.61 g CO_2/MJ.

Table 1.06. CO_2 Emissions by Fuel Type (does not include other GHGs).

Fuel Type	g CO_2/mmBtu	g CO_2/MJ
Crude oil	10	0.01
Residual oil	12	0.01
Diesel fuel	174	0.17
Gasoline	17	0.02
Natural Gas	4,413	4.18
Coke (Pet. Coke)	176	0.17
Electricity	0	0
Natural Gas (flared)	761	0.72
Total	**5,564**	**5.27**

Table 1.07 utilizes the energy use by fuel type from Table 1.02 and calculates GHG emissions utilizing emission factors which are provided in Table 1.08. The CO_2 emission factors represent the carbon in fuel minus carbon emissions

associated with VOC and CO emissions. Thus, the emission factor is different among equipment types such as engines and turbines. The carbon in fuel factors are CA-GREET default values, except for natural gas, which is slightly different based on the AB 1007[2] analysis. However, the calculations in the fuel cycle reflect the estimated direct emissions of CO_2 from the different equipment types excluding the carbon in VOC and CO. Note that energy use is used from Table 1.02 of this document (as an example, the value 124 is from Table 1.02 for crude oil). Table 1.08 essentially provides details on how CO_2 emissions were calculated and provided in Table 1.07.

Table 1.07. Specific Fuel Shares Contributing to CO_2 Emissions (see Table 1.06)

Fuel	Calculations	CO_2 emissions (g CO_2/mmBtu)
Crude Oil	124 *(crude oil emissions factor + total CO_2 emissions from crude recovery)/ 10^6	10
Residual Oil	124 *(Fraction of residual oil consumed in a commercial boiler*emissions factor of a commercial boiler + emissions from crude*loss factor for emissions from crude + total emissions from residual oil)/ 10^6	12
Diesel fuel	1,867*(percentage from diesel boiler*emission factor for diesel boiler + percentage from stationary diesel engine*emissions factor for diesel engine + percentage from stationary diesel turbine*emission factor of diesel turbine + emissions from crude*loss factor + total emissions from diesel)/ 10^6 (see Table 1.08A for further details)	174
Gasoline	249*(emissions factor of reciprocating engine + crude emissions* loss factor + emissions from conventional gasoline)/ 10^6	17
Natural Gas	70,595*(percentage of natural gas used in an engine*emissions factor for natural gas engine + percentage of natural gas used in a small industrial boiler*emissions factor for small industrial boiler + emissions from natural gas as a stationary fuel)/10^6 (see Table 1.08B for further details)	4,413
Coal (Pet. Coke)	1803*(emission factor for coal boiler + WTT emissions for coal)	176
Electricity	0*(emissions from producing feedstock + emissions from consuming feedstock)/10^6	0
Natural Gas (flared)	13,107*(emissions factor for natural gas flaring)/10^6	761

Table 1.08. Values Used in Table 1.07

Fuel	Calculations
Crude Oil	Crude oil emission factor = 77,264 (g CO_2/mmBtu) which is a CA-GREET default.
	CO_2 emissions from crude recovery = 5,564 (g CO_2/mmBtu) which is recursively calculated from Table 1.06.
Residual Oil	Fraction of residual oil consumed in a commercial boiler = 1.00 which is a CA-GREET default value.
	Emission factor of a commercial boiler = 85,049 in g CO_2/mmBtu which is a CA-GREET calculated value.
	WTT Emission for crude = 6,743 in g CO_2/mmBtu which is a CA-GREET calculated value.
	Loss factor for emissions from crude = 1.0000 also a CA-GREET default value.
	WTT emissions from residual oil = 5,427 a CA-GREET calculated value.
Diesel fuel	Percentage from diesel boiler = 25.0% a default value from CA-GREET.
	Emission factor for diesel boiler = 78,167 g CO_2/mmBtu, a CA-GREET calculated value.
	Percentage from stationary diesel engine = 50.0%, a CA-GREET default value.
	Emission factor for diesel engine = 77,349 g CO_2/mmBtu, a calculated value from CA-GREET.
	Percentage from stationary diesel turbine = 25.0% a default CA-GREET value.
	Emission factor of diesel turbine = 78,179 g CO_2/mmBtu, a CA-GREET calculated value.
	Emissions from crude = 6743 g CO_2/mmBtu, calculated from CA-GREET.
	Loss factor for emissions from crude = 1.0000, a default value from CA-GREET.
	Total emissions from diesel = 9,048 g CO_2/mmBtu, a CA-GREET calculated value.
Gasoline	Emission factor of reciprocating engine = 50,480 g CO_2/mmBtu a CA-GREET default value.
	Emissions from crude = 6743 g CO_2/mmBtu, a CA-GREET calculated value.
	Loss factor for emissions from crude = 1.0000, a CA-GREET default value.
	Emissions from conventional gasoline = 11,671 g CO_2/mmBtu, CA-GREET calculated value.
Natural Gas	Percentage of natural gas used in an engine = 50.0%, CA-GREET default.
	Emission factor for natural gas engine = 56,551 g CO_2/mmBtu, a CA-GREET calculated value
	Percentage of natural gas used in a small industrial boiler = 50.0%, a CA-GREET default.
	Emissions factor for small industrial boiler = 58,176 g CO_2/mmBtu, a CA-GREET calculated value
	Emissions from natural gas as a stationary fuel = 5,155 g CO_2/mmBtu, a CA-GREET calculated value.
Coke (Pet.	Emission factor for coal boiler = 96,299 g/mmBtu, a CA-GREET

Coke)	calculated value
	Emissions from natural gas a processing fuel = 1,505 g/mmBtu
Electricity	Emissions from producing feedstock = 14,305 g CO_2/mmBtu, a CA-GREET calculated value from electricity pathway.
	Emissions from consuming feedstock = 162,627 g CO_2/mmBtu, a CA-GREET calculated from electricity pathway.
Natural Gas (flared)	Emissions factor for natural gas flaring =58,048 g CO_2/mmBtu, a CA-GREET default value.

Tables 1.09A and 1.09B provide additional details on emissions resulting from use of diesel, natural gas and electricity generation. CO_2 emissions from crude oil, residual oil, and gasoline combustion cannot be further broken down according to equipment type because they are used in only one equipment type: industrial boilers (crude oil and residual oil) and reciprocating engines (gasoline). The values from crude oil, residual oil, and gasoline combustion are provided by the emission factors for these fuels as detailed in Tables 1.07 and 1.08. In Tables 1.09A and 1.09B, details for CO_2 emissions are provided for diesel and natural gas used as a fuel in crude recovery operations. All values in Tables 1.09A and 1.09B are CA-GREET default values and subsequent CA-GREET calculated values. Note that Tables 1.09A and 1.09B detail how values reported in Table 1.07 for diesel and natural gas are calculated.

Table 1.09A. CO_2 Emissions from Diesel

Equipment Type	**Equipment Shares**	**Emissions Factor (g/mmBtu)**	**g CO_2/mmBtu**
Commercial Boiler	25%	78,167	36
Stationary Reciprocating Engine	50%	77,349	72
Turbine	25%	78,179	36
Crude Oil and Diesel Production			29
Total			**174**

Table 1.09B. CO_2 Emissions from Natural Gas

Equipment Type	Equipment Shares	Emissions Factor	g CO_2/mmBtu
Stationary Reciprocating Engine	50%	56,551	1,996
Small Industrial Boiler	50%	58,176	2,053
As Stationary Fuel		5,349	364
Total			**4,413**

Tables 1.10 through 1.13 are detail CO_2 emissions from electricity generation. The emissions factor is CA-GREET calculations. For electricity, it is broken down into emissions from feedstock production (recovering feedstock such as coal from mines and transporting to a facility) and feedstock consumption (actual use in a boiler). Table 1.10 details the net and individual equipment generation efficiencies and upstream energy for natural gas based electricity.

Table 1.10. Energy Breakdown from Electricity (Feedstock Consumption)

Fuel	Conv. Efficiency	Generation Mix	Relationship of Conversion Efficiency and Energy Use	Energy Use (Btu/mm Btu)	Description
Nat. Gas	39.0%	100%	$(10^6/0.394)*(1/1-0.081)$	2,793,243	Energy used as natural gas (Btu/mmBtu), a CA-GREET calculation

Table 1.11 summarizes upstream CO_2 emissions from feedstock production related to electricity

Table 1.11. Detailed CO_2 Emissions from Feedstock Production

Feedstock	Calculation	g CO_2/mmBtu
Natural Gas	$9{,}971*(2{,}793{,}243*5{,}084)/10^6)/10^6$	142

Where 9,971 Btu/mmBtu is the electricity input, 2,793,243 Btu/mmBtu is the fuel cycle electricity energy and 5,084 g-CO_2/mmBtu electricity is the fuel cycle CO_2 emissions for natural gas destined for electricity production.

Table 1.12 provides details on CH_4, N_2O, VOC and CO emissions generated during the combustion of the different fuels listed in these tables. These values are calculated from default CA-GREET values for sources that are used in crude recovery.

Table 1.12. CH_4, N_2O, VOC and CO Emissions from Crude Recovery

Fuel Type (g /mmBtu)	CH_4	N_2O	VOC	CO
Crude oil	0.003	0.000	0.000	0.005
Residual oil	0.014	0.000	0.001	0.005
Diesel fuel	0.220	0.003	0.097	0.398
Gasoline	0.053	0.001	0.449	3.262
Natural gas	22.158	0.069	1.981	13.914
Electricity	0.000	0.000	0.000	0.000
Natural gas (flared)	0.642	0.014	0.033	0.341
Total (without non-combustion)	23.090	0.088	2.561	17.925
Non-combustion	11.0		0.702	
Vented	54.2			
Total	**88.29**	**0.088**	**3.263**	**17.925**

Table 1.13 summarizes the total GHG emissions for crude recovery. The total is calculated as g CO_2e where non-CO_2 GHG gasses have been converted to CO_2 equivalents using their GWP detailed earlier. It also shows how CA-GREET account for CO and VOC emissions in its calculation of pathway GHG emissions. The electricity emission credit is equal the net electricity export in J/J crude multiplied by the fuel cycle GHG emissions associated with 100% NG (124.1 g/MJ):

(-0.0041 J net electricity/J crude)*(124.10 gCO_2/MJ) = -0.51 gCO_2/MJ.

Note: 124.10 gCO_2/MJ is the pathway carbon intensity for average CA electricity. Please refer to the "Electricity" pathway document for details on this value.

Table 1.13. Total GHG emissions from Crude Recovery

	(g/mmBtu)	Formula	gCO_2e/mmBtu	gCO_2e/MJ
CO_2	5,564	5,564*1	5,564	5.27
CH_4	88.290	88,290*25	2207.253	2.09
N_2O	0.088	0.088*298	26.095	0.03
CO	17.925	17.925*0.43*(44/12)	28.168	0.03
VOC	3.263	3.263*0.85*(44/12)	10.169	0.01
Total GHG emissions			**7,836**	**7.43**
Electricity Co-Product Credit				**-0.51**
Total GHG emissions				**6.93**

Section 2. CRUDE TRANSPORT

2.1 Energy Use for Crude Transport

Crude transportation energy use is based on the weighted mix for crude recovery (average CA crude) and the corresponding transport mode. Table 2.01 provides details on the various modes of transport for crude used in CA refineries. The electricity mix is assumed to be 100% NG-based. The transport distances have been calculated to be 442 miles via pipeline, 7,063 miles via oil tanker, and 200 miles via barge.

Table 2.01. Crude Oil Transport Details

		Crude Pipeline			**Ocean Tanker**		
Crude Supply (2005)	Mix	Dest.	Source Share	Distance (miles)	Dest.	Source Share	Distance (miles)
Alaska	16.1%	Valdez	100%	870	SF	100%	1,974
Domestic	38.9%	Refineries	100%	200	-		-
Foreign	45.0%	Weighted Calc.	100%	498	Weighted Calc.	100%	8,884
Annual Total		Weighted Average		442	Weighted Average		7,063

	Barge		
Crude Supply (2005)	Destination	Source Share	Distance (miles)
Alaska			
Domestic	CA	5.0%	200
Foreign			
Annual Total	Weighted Average	1.9%	200

Transport distance for imported foreign oil is based on California Energy Commission's summary of Energy Information Agency data for crude oil sources combined with transport distances determined from the shipping's[8] on-line calculator.

The average pipeline and ocean tanker distances and average barge share were calculated using the weighted consumption data in Table 2.01 and shown below:

- Average Pipeline Distance: 442 mi = (870*16.1%) + (200*38.9%) + (498*45.0%)
- Average Ocean Tanker Distance: 7,063 mi = [(1,974*16.1%) + (8,884*45.0%)]/(16.1% + 45.0%)
- Average Barge Distance: 200 mi = (38.9%*5.0%*200)/(38.9%*5%)
  Average Barge Average Share: 1.9% = (38.9%)*(5.0%)

Note: The average barge share must be calculated separately and input into CA-GREET as one number because GREET only has one input for barge share.

The three modes of transport are utilized to transport crude to California refineries. Details of how energy use is calculated for both types of modes of transport appear in Table 2.02 below with values used in the calculation provided in Table 2.03. Both modes utilize common factors such as lower heating values (LHV) and density of crude, and transport mode specific factors such as energy consumed per mile of transport to calculate energy use for specific distances transported.

Table 2.02. Details of Energy Consumed for Crude Transport

	Detailed Calculations	**Btu/mmBtu**
Feed Loss	CA-GREET default	62
Ocean Tanker	(% Fuel Transported by Ocean Tanker)*(Density of crude/LHV of crude)*(Energy Intensity Origin to Destination plus Return Trip)*(Average Miles Traveled)* (1/454)* (1/2000)*(1+0.169)*10^6	7,104
Pipeline	(% Fuel Transported by Pipeline)*(Density of crude/LHV of crude)*(Energy consumed)*(miles traveled)*(1/454) *(1/2000)*(1 + 2.986))*10^6	9,073
Barge	(% Fuel Transported by Barge)*(Density of crude/LHV of crude)*(Energy Intensity Origin to Destination plus Return Trip)*(miles traveled)*(1/454)*(1/2000)*(1+0.169)*10^6	88
Total	**Crude Recovery**	**16,265**

Table 2.03. Values for formulas in Table 2.02

Description	**Value**	**Source**
Weighted average distance traveled by ocean tanker (mi)	7,063	Table 2.01
Weighted average distance traveled by pipeline (mi)	442	Table 2.01
Distance traveled by Barge (mi)	200	Table 2.01
Density of crude (grams/gallon)	3,205	CA-GREET default
Lower heating value (LHV) of crude (Btu/gallon)	129,670	CA-GREET default
Ocean tanker energy intensity (Btu/ton-mile)	27 24 (return trip)	CA-GREET calculation
Pipeline energy intensity (Btu/ton-mile)	253	CA-GREET default
Barge energy intensity (Btu/ton-mile)	403 307 (return trip)	CA-GREET default
Conversion from pounds to grams	454	
Conversion from tons to pounds	2,000	
WTT Energy Factor for Residual Oil (Btu/Btu)	0.169	CA-GREET calculation
WTT Energy Factor for Electricity including electricity (Btu/Btu)	2.986	CA-GREET calculation

2.2 GHG Emissions for Crude Transportation

Table 2.04 details CO_2 emissions related to crude transport and distribution. These calculations assume 7,063 miles for ocean tankers and 442 miles for pipelines, as detailed in section 2.1. Table 2.05 provides values for various terms used in Table 2.04.

Table 2.04. Crude Transport CO_2 Emissions

Mode	Formula	gCO_2/mmBtu	gCO_2/MJ
Ocean Tanker	(Density of crude/LHV of crude)*(miles traveled) *(1/454)*(1/2000)*((Energy intensity on trip from origin to destination*(emission factor for residual oil+ WTT CO_2 for residual oil)) + (Energy intensity on return trip* (emission factor for bunker fuel + emission factor for residual oil))	586	0.56
Pipeline	(Density of crude/LHV of crude)*(Energy intensity of pipeline)*(miles traveled)*(1/454)*(1/2000) *(WTT emissions for electricity)	538	0.51
Barge	(Density of crude/LHV of crude)*(miles traveled) *(1/454)*(1/2000)*((Energy intensity on trip from origin to destination*(emission factor for residual oil + WTT residual oil CO_2)) + (Energy intensity on return trip*(emission factor for residual oil + WTT residual oil CO_2))	7	0.01
	Total	**1,131**	**1.07**

Table 2.05. Values of Properties Used in Table 2.04

Parameters	Values	Sources
Miles traveled by Ocean Tanker (miles)	7,063	Table 2.01
Pipeline transport (miles)	442	Table 2.01
Density of crude (grams/gallon)	3,205	CA-GREET default
Lower heating value (LHV) of crude (Btu/gallon)	129,670	CA-GREET default
Energy intensity of Ocean Tanker on trip to destination (Btu/ton-mile)	27	CA-GREET default
Energy intensity of Ocean Tanker on return trip (Btu/ton-mile)	24	CA-GREET default
Energy intensity of Pipeline (Btu/ton-mile)	253	CA-GREET default
Energy intensity of Barge on trip to destination (Btu/ton-mile)	403	CA-GREET default
Energy intensity of Barge on trip to destination (Btu/ton-mile)	307	CA-GREET default
Conversion from pounds to grams	454	
Conversion from tons to pounds	2,000	
Conversion from MJ to mmBtu	1055	
CO_2 EF for residual oil in barge (g/mmBtu fuel burned)	84,515 (both trips)	CA-GREET default
WTT electricity CO_2 emissions (g/mmBtu)	176,891	CA-GREET calculated
WTT Emission factor for Residual Oil (g/mmBtu)	11,920	CA-GREET default

Table 2.06 details CH_4 emissions for crude transport and distribution utilizing ocean tanker and pipeline transport modes. The emissions are CA-GREET defaults. VOC, CO, and N_2O emissions are small for this group and not detailed, but are included in the total GHG emissions calculations for this part and shown in Table 2.07.

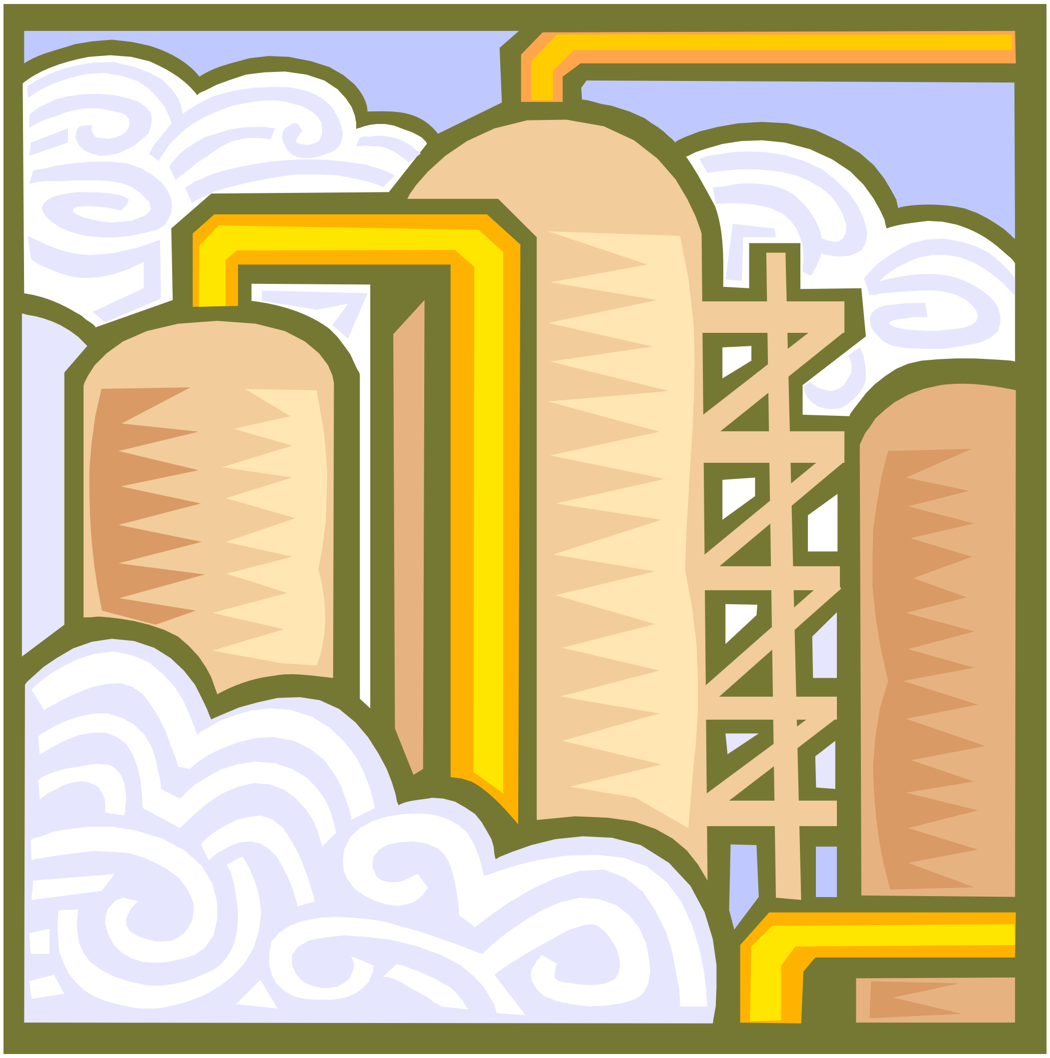
Table 2.06. Crude Transport CH_4 Emissions

	g CH_4/mmBtu
Ocean Tanker (residual oil)	0.699
Pipeline (electricity)	1.121
Barge	0.008
Total	**1.83**

Table 2.07. Total GHG Emissions Crude Transport and Distribution

GHG	(g/mmBtu)	Formula to convert to CO_2e	g CO_2e/mmBtu	g CO_2e/MJ
CO_2	1,131	1,131*1	1,131	1.07
CH_4	1.829	1.829*25	46	0.04
N_2O	0.024	0.024*298	7	0.01
CO	1.601	1.601*0.43*(44/12)	3	0.00
VOC	0.619	0.619*0.85*(44/12)	2	0.00
Total GHG emissions				**1.14**

Section 3. CRUDE REFINING



3.1 Energy Use for Crude Refining

Wang et al.[8] analyzed refining efficiency on a process allocation basis and, based on this analysis, calculated energy efficiency for the various fuels produced from a crude refining facility. The refinery efficiency is based on a model refinery result combined with EIA data for petroleum production. The 84.5% refinery efficiency value for CARBOB is based on the AB 1007 report[2] and is consistent with other well to wheel studies. This refinery efficiency takes into account additional energy used to depentanize gasoline and additional hydrogen required for sulfur removal. Figure 3 is derived from Wang et al.[9] and provides refining efficiencies for the various streams exiting a modern refinery.

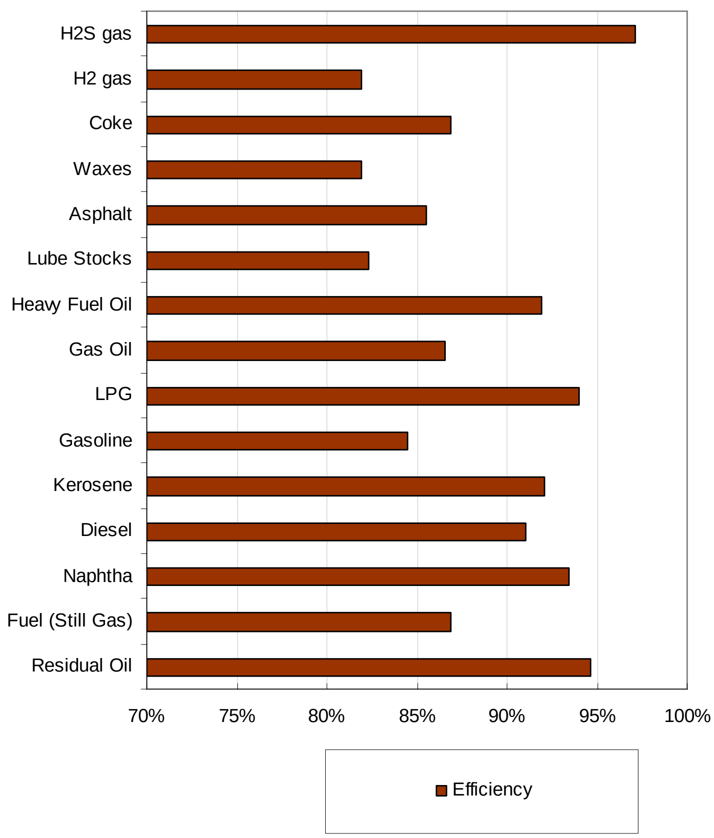


Figure 3. Efficiency of Various Fuel Productions

The AB 1007 study used an average gasoline refining efficiency of 84.5% from the study above which is for average CA crude. This value is used to calculate the energy inputs necessary for gasoline as detailed in Table 3.01. The CA average electricity mix is assumed for refining (see Electricity pathway document for energy use and emissions details).

Table 3.01. Details on How Efficiency is Used to Calculate Energy Needs for Crude Refining

Fuel Type	**Fuel Shares**	**Relationship of Refinery Efficiency (0.845) and Fuel Shares**	**Btu/mmBtu Fuel**
Residual Oil	3%	(1,000,000)(1/0.845 – 1)(0.03)	5,503
Natural Gas	30%	(1,000,000)(1/0.845 – 1) (0.30)	55,030
Pet Coke	13%	(1,000,000)(1/0.845 – 1) (0.13)	23,846
Electricity	4%	(1,000,000)(1/0.845 – 1)(0.04)	7,337
Refinery Still Gas	50%	(1,000,000)(1/0.845 – 1)(0.50)	91,716
Total	**100%**		**183,432**

The values in Table 3.01 are adjusted to account for upstream WTT energy use. Table 3.02 depicts the adjustments to the values from the table above for each fuel type accounting for loss factors associated with the WTT energy for each fuel used during crude refining operations. Table 3.03 details the values and descriptions for the formulas presented in Table 3.02.

Table 3.02. Adjustment to Crude Refining to Account for Loss Factors and Other Factors

Fuel Type	**Formula**	**Btu/mmBtu**
Residual Oil	$5{,}503*(1 + (A*B+C/10^6))$	6,421
Natural Gas	$55{,}030*(1 + D/ 10^6)$	58,841
Pet. Coke	$23{,}846*(1 + E/ 10^6)$	24,321
Electricity	$7{,}337*((F+G)/ 10^6)$	16,682
Refinery still gas	$91{,}716*(1 + (A/ 10^6))$	100,107
Total energy for refining		**206,372**

Table 3.03. Details for Entries in Table 3.02

Quantity	Description
A = 91,493	Energy required to produce crude as feedstock for use in US refineries, a CA-GREET calculated value. (Btu/mmBtu)
B = 1.0000	Loss factor, a CA-GREET default.
C = 75,286	Energy in Btu required to produce 1 million Btu of residual oil, a CA-GREET calculated value.
D = 69,327	Energy required to produce natural gas as a stationary fuel, a CA-GREET calculated value.
E = 19,910	Total energy required to produce Pet. Coke for refining.
F = 100,413	Total energy required to produce feedstock for power generation, calculated in CA-GREET electricity analysis.
G = 2,173,222	Energy required in Btu to produce one million Btu of electricity which is calculated in CA-GREET electricity analysis.

3.2 GHG Emissions from Crude Refining

The transformation of energy from the various fuels above to useful energy required in the processing of crude to CARBOB generates equipment specific GHG emissions. GHG emissions include CO_2 as well as non-CO_2 GHG gases. This document first presents the CO_2 emissions, followed by non-CO_2 emissions, which are then converted to CO_2 equivalents and summarized at the end of this section (section 3.2).

Table 3.04 lists CO_2 emissions by fuel type generated during the refining of crude to CARBOB. Tables 3.05 and 3.06 provide details of CO_2 emissions related to use of residual oil in refineries for processing crude to CARBOB.

Table 3.04. CO_2 Emissions by Fuel Type

Fuel Type	(g CO_2/mmBtu)	(g CO_{2e}/MJ)
Residual oil	533	0.50
Natural gas	3,482	3.30
Coal	2,332	2.21
Electricity	917	0.87
Refinery Still Gas	5,337	5.06
Total	**12,600**	**11.94**

Table 3.05. CO_2 Emissions from Residual Oil Use in Refineries from Table 3.04

Calculation Details	g CO_2/mmBtu	Reference
5,503*(emissions factor for an industrial residual oil boiler*Loss Factor + emissions from residual oil + emissions from crude oil)/10^6	533	CA-GREET default

Table 3.06. Values for use in Table 3.05

Factor	Value	Reference
Emissions factor for an industrial residual oil boiler	85,045 g CO_2/mmBtu	CA-GREET default
Residual oil loss factor	1.0000	CA-GREET default
Emissions from residual oil	5,292 grams CO_2/mmBtu	CA-GREET default
Emissions from crude oil	6,470 grams CO_2/mmBtu	CA-GREET default

Tables 3.07 and 3.08 provide details on CO_2 emissions from natural gas use in crude refining to CARBOB.

Table 3.07. CO_2 Emissions from Natural Gas from Table 3.04

Calculation details	g CO_2/mmBtu	Reference
55,030*(share from NG engine*emission factor for NG engine)+(share from large turbine*emission factor for large turbine +(share from large industrial boiler*emission factor for large industrial boiler) + (share from small industrial boiler *emission factor for small industrial boiler) + Emissions from natural gas as a stationary fuel/10^6	3,482	CA-GREET default

Table 3.08. Details of Values Used in Table 3.07

	Shares	**Emissions Factors ($g\ CO_2$/mmBtu)**	**Reference**
Share from natural gas engine	0%	56,551	CA-GREET default
Share from large turbine	25%	58,179	CA-GREET default
Share from large industrial boiler	60%	58,198	CA-GREET default
Share from small industrial boiler	15%	58,176	CA-GREET default
Emissions from natural gas as a stationary fuel		3,482	CA-GREET default

Electricity contributions to GHG emissions are provided in Tables 3.09 to 3.15, both for feedstock production and feedstock consumption.

Table 3.09. CO_2 Emissions from Electricity from Table 3.04

	Details Calculation	**$g\ CO_2$/mmBtu**
Electricity as feedstock	$7,337*7,116/10^6$	54
Electricity as fuels	$7,337*117,633/10^6$	863
Total		**917**

Note: 7,337 Btu/mmBtu is energy of electricity used in CARBOB refining (see table 3.01)

To calculate CO_2 emissions above:
CO_2 emission from power plant + VOC and CO emissions conversion from power plant, where:

- CO_2 from power plant = 7,337*(Specific Power Plant Emission Factor)* % of generation mix/(1- % assumed loss in transmission)/10^6, then convert from g/kWh to gCO_2e/mmBtu by multiplying g/kWhr by (10^6/3,412).
- VOC and CO conversion are from CA-GREET defaults.

Table 3.10. Type of Power Generation Plant and Associated Emission Factors

Power Plant Type	**Generation Mix**	**CO_2 Emission Factor** (g/kWhr)	**Loss in transmission**
Oil-fired	0.1%	907	8.1%
Nat. Gas-fired	43.1%	554	8.1%
Coal-fired	15.4%	1,050	8.1%
Nuclear	14.8%	0	8.1%
Biomass	1.1%	0	8.1%
Renewables	25.6%	0	8.1%

Table 3.11 provides a breakdown of CO_2 emissions from electricity generation into feedstock production and feedstock consumption (as fuels). Production refers to mining or other methods to actually procure the feedstock necessary for use in electricity generation. Feedstock production accounts for about 5.3% of the total emissions and feedstock consumption to generate electricity accounts for the balance of 94.7%.

Table 3.11. CO_2 Emissions from Electricity

	gCO_2/mmBtu	% share
Feedstock Production	7,342	5.9%
Feedstock Consumption	117,633	94.1%
Total	**124,975**	

CARBOB refining also results in CO_2 emissions from vented sources (non-combustion), as shown in Table 3.12.

Table 3.12. CO_2 Emissions from Non-Combustion Sources

	gCO_2/mmBtu	gCO_2e/MJ
Non-combustion	1,477	1.40

This is calculated from assumed CO_2 vented from bulk terminals (1,172 g/mmBtu) and ratio efficiencies of conventional gasoline refining (87.7%) on CARBOB refining (84.5%): 1,172*(1-87.7%)/(1-84.5%).

Table 3.13 and 3.14 provide details of CO_2 emissions related to feedstock electricity production.

Table 3.13. CO_2 Emissions from Electricity (feedstock production)

Fuel Share	Relationship of Energy Use and CO_2 Emissions	Energy Use Emissions g CO_2/mmBtu
Residual oil	1,563*(crude emission factor*crude loss factor + residual oil emission factor)/10^6	18
Natural gas	1,203,888*(natural gas emission factor)/ 10^6	6,017
Coal	491,418*(coal emission factor)/ 10^6	731
Biomass	37,288*(biomass emission factor)/farmed trees heating value	88.2
Nuclear	161,045*(uranium emission factor)/(conversion factor for nuclear power plants*1000*3412)	424
Other*	VOC emissions*Carbon ration of VOC/Carbon ratio of CO_2 + CO emissions*Carbon ration of CO/Carbon ratio of CO_2	63
Total		**7,342**

* “Other” is a combination of hydro, wind, geothermal, etc.

The numerical values used in the table above are the energies from those feedstocks used at power plants to generate one mmBtu of electricity at the use site (see Table 1.10).

Table 3.14. Factors and Values for Use in Table 3.13

Description	CA-GREET worksheets	CA-GREET default values
Crude WTT emissions (to U.S refineries)	*Petroleum* worksheet	6,579 g CO_2/mmBtu
Crude loss factor		1.000
Residual oil WTT emissions	*Petroleum* worksheet	5,292 g CO_2/mmBtu
Natural gas WTT emissions	*NG* worksheet	5,079 g CO_2/mmBtu
Coal WTT emissions	*Coal* worksheet	1,487 g CO_2/mmBtu
Biomass WTT emissions (Farmed Trees) (sum of factors for trees farming, fertilizer, pesticides, and trees T&D)	*EtOH* worksheet	17,623 g CO_2/mmBtu
Farmed trees heating value (LHV, Btu/ton)	*Fuel_Specs* worksheet	16,811,000 Btu/ton
Uranium WTT CO_2 emissions	*Uranium* worksheet	62,270 g CO_2/mmBtu
Conversion factor for nuclear power plants		6.926 MWh/g of U-235
Carbon Ratio of VOC		0.85
Carbon Ratio of CO		0.43
Carbon Ratio of CO_2 (12/44)		0.27

Table 3.15 shows the relationship between the energies used from feedstocks at a power plant (to produce one mmBtu of electricity to the use site) and the conversion efficiencies of electrical generation for each feedstock used, after taking into account the loss (8.1%) from the transmission of electricity.

Table 3.15. Energy Breakdown from Electricity (Feedstock Consumption)

Fuel Shares	Conversion Efficiency	Generation Mix	Relationship of Conversion Efficiency and Energy Use	Energy Use (Btu/mmBtu
Residual oil	34.8%	0.05%	$(10^6/0.348)*(1/1-0.081)*0.0005$	1,563
Natural gas	39.0%	43.1%	$(10^6/0.390)*(1/1-0.081)*0.431$	1,203,888
Coal	34.1%	15.4%	$(10^6/0.341)*(1/1-0.081)*0.154$	491,418
Biomass	32.1%	1.1%	$(10^6/0.321)*(1/1-0.081)*0.011$	37,288
Nuclear	100%	14.8%	$(10^6/1.00)*(1/1-0.081)*0.148$	161,045
Others*	100%	25.6%	$(10^6/1.00)*(1/1-0.081)*0.255$	278,020
Total				**2,173,222**

* "Others" is a combination of hydro, wind, geothermal, etc.

Tables 3.16 and 3.17 detail CO_2 emissions from use of refinery still gas in crude refining operations.

Table 3.16. CO_2 Emissions from Use of Refinery Still Gas

Calculation	Value (g CO_2/mmBtu)	Reference
Emissions from refinery still gas as a stationary fuel* (share from engine*natural gas engine emission factor) + (share from large turbine*emission factor for large natural gas turbine) + (share from large industrial boiler*emission factor for large industrial boiler) + (share from small industrial boiler *emission factor for small industrial boiler) + (Emissions from natural gas as a stationary fuel)/10^6	5,337	CA-GREET default calculation

Table 3.17. Values Used in Table 3.16

Description	Shares	Emission Factor (g CO_2/mmBtu)	Reference
Natural Gas, engine	0	56,551	CA-GREET default
Natural Gas, large turbine	25%	58,179	CA-GREET default
Natural Gas, large Industrial boiler	60%	58,198	CA-GREET default
Natural Gas, small Industrial boiler	15%	58,176	CA-GREET default
Emissions from natural gas as a stationary fuel		5,088	CA-GREET default

CH_4 emissions and N_2O emissions from crude refining are shown in Tables 3.18 and 3.19. VOC and CO contributions are small and not further detailed here. They are however included in Table 3.20 below.

Table 3.18. CH_4 Emissions Converted to CO_2e

Fuels	g CH_4/mmBtu	g CO_2e/MJ
Residual oil	0.624	0.01
Natural gas	7.192	0.17
Coal	2.886	0.07
Electricity	1.614	0.04
Refinery Still Gas	0.173	0.00
Total	**12.49**	**0.30**

Table 3.19. N_2O Emissions

Fuel	g N_2O/mmBtu	g CO_2e/MJ
Residual oil	0.003	0.00
Natural gas	0.037	0.01
Coal	0.014	0.00
Electricity	0.016	0.00
Refinery Still Gas	0.056	0.02
Total	**0.126**	**0.04**

Table 3.20 summarizes the total GHG emissions from crude refining. Note that non-CO_2 gases have been converted to CO_2 equivalents using conversion factors detailed earlier in this document.

Table 3.20. GHG Emissions from Crude Refining

GHG	(g/mmBtu)	Conversion to CO_2e	g CO_2e/mmBtu	g CO_2e/MJ
CO_2	12,600	12,600 *1	12,600	11.94
CH_4 (combustion)	12.489	12.489*25	312	0.30
N_2O	0.126	0.126*298	38	0.04
CO	6.994	6.994*0.43 *(44/12)	11	0.01
VOC	0.944	0.944*0.85*(44/12)	3	0.00
Non-combustion CO_2			1,477	1.40
Non-combustion VOC			3.764	< 0.01
Non-combustion CO			3.733	< 0.01
Total				**13.72**

Section 4. CARBOB TRANSPORT AND DISTRIBUTION

4.1 Energy Use for Transport and Distribution of CARBOB

Table 4.01 shows the energy inputs used in transporting CARBOB to trucking terminals. The energy intensity of 253 Btu/ton-mi is a default CA-GREET value based on a composite of natural gas compressor prime movers. The 50 mile distance is based on an average for California pipeline delivery and is documented in the AB 1007 report. The fuel shares input assumption is 100% electric motors based on the AB 1007 analysis of petroleum infrastructure in California. The energy intensity is multiplied by an adjustment factor for each type of pipeline motor. In this case the electric motor adjustment factor is 100% (a CA-GREET default value). The total energy is then calculated, including the WTT energy to produce electricity.

Table 4.02 shows the energy inputs for truck transport. The calculation is based on a tanker truck capacity of 9,000 gallons (25 metric tons) and a transport distance of 50 miles. The 50 mile distance is based on a survey of California fuel delivery trucks and is documented in the AB 1007 report. CA-GREET calculates the diesel energy per ton-mile based on the cargo capacity of the truck and its fuel economy.

Table 4.03 shows the total energy calculations used in CA-GREET. Here the pipeline and truck values are weighted by the fraction of fuel delivered by each mode. 80% of the gasoline is assumed to be piped to a blending terminal because some refineries fill trucks at the loading rack adjacent to the refinery. 99.4% of the gasoline is assumed to be transported to fueling stations by delivery trucks. The remaining 0.6% corresponds to the few fueling stations where gasoline is provided directly by pipeline. Table 4.04 details the values used in the formulas presented in Table 4.03. The total transport energy for CARBOB shown in Table 4.03 includes energy associated with feed loss, which is calculated based on the VOC emissions (g/mmBtu) from the bulk terminal and refinery stations (see note below Table 4.03).

Table 4.01. Energy use for Transport and Distribution via Pipeline

	Energy Intensity (Btu/ton-mile)	**Distance from Origin to Destination (miles)**	**Type of Power Generation**	**Shares of the type of turbine used**	**Distributed by pipeline**
Pipeline	253	50	Electric Motor	100 %	80%*

*Assumed 20% transported directly from refinery terminal rack

Table 4.02. Energy use for Transportation and Distribution CARBOB via HDD Truck

	Energy Intensity (Btu/ton-mile)	Distance from Origin to Dest. (miles)	Capacity (tons)	Fuel Used (miles/gal)	Energy Used by HDD truck (Btu/ mile)	Share of Diesel used	Transp/ Dist. by truck
HDD Truck Transport	1,028	50	25	5	25,690	100%	20%
HDD Truck Distribution	1,028	50	25	5	25,690	100%	99.4%*

* Assumed 0.6% CARBOB is transported directly by pipeline to about 50 stations

Table 4.03. Details of Energy Uses for CARBOB Transportation and Distribution

Transport mode	Details Calculations	Btu/ mmBtu
Feed Loss	(Loss Factor – 1)*10^6	813
CARBOB transported by pipeline	(Density of CARBOB/LHV of CARBOB)*(1/454)*(1/2000)*(energy consumed by pipeline)*(miles transported one-way)*100%*100%*(2.276)*80%*10^6	642
CARBOB Transport by HDD truck	(Density of CARBOB/LHV of CARBOB)*(1/454)*(1/2000)*(energy consumed by HDD truck)*(miles transported one-way+ miles transported one-way backhaul)*100%*(1+0.232)*20%*10^6	699
CARBOB Distribution by HDD truck	(Density of CARBOB/LHV of CARBOB)*(1/454)*(1/2000)*(energy consumed by HDD truck)*(miles transported one-way+ miles transported one-way backhaul)*100%*(1+0.232)*99.4%*10^6	3,477
Total		**5,632**

Note: Loss factor = [(VOC from bulk terminal + VOC from refinery stations)/CARBOB Density)*(CARBOB LHV/10^6)] + 1

Table 4.04. Values of Properties Used in Table 4.03

Properties	Values	Source
Feed loss (Btu/mmBtu)	813	CA-GREET calculation
Lower heating value of CARBOB (Btu/gallon)	113,300	AB 1007 value
Density of CARBOB (grams/gallon)	2,819	CA-GREET default
Energy consumed by Pipeline (Btu/ton-mile)	253	CA-GREET default
Conversion from pounds to grams	454	
Conversion from tons to pounds	2,000	
Energy intensity of CARBOB transported by HDD truck (Btu/ton-mile)	1,028	AB 1007 value
CARBOB transport one-way (mile)	50	AB 1007 value
Energy consumed in electricity used as transportation fuel in CARBOB Production (Btu/Btu)	2.274	CA-GREET calculation
Energy consumed in diesel used as transportation fuel in CARBOB Production (Btu/Btu)	0.217	CA-GREET calculation
VOC from bulk terminal (g/mmBtu)	6.667	CA-GREET default
VOC from refinery stations (g/mmBtu)	13.082	CA-GREET default

Note:

- 2.276 is the WTT energy for electricity calculated in CA-GREET = (energy consumed to produce feedstock + Energy consumed to produce electricity)/106 = $(2{,}173{,}222+102{,}959)/10^6$
- 0.228 is the diesel adjustment factor = energy of crude oil transported to the US refineries*loss factor of diesel + WTT energy of conventional diesel.

4.2 GHG Emissions for Transportation and Distribution of CARBOB

Table 4.05 details only CO_2 emissions for the transport and distribution of finished CARBOB.

Table 4.05. CO_2 from CARBOB Transportation and Distribution

	Miles traveled 1-way	Energy Intensity (Btu/mile-ton)	Assumed % usage	CO_2 (g/mmBtu)	CO_2e (g/MJ)
Transported by Pipeline	50	253	80%	35	0.03
Transport by HDD Truck	50	1028	20%	53	0.05
Distributed by HDD Truck	50	1028	99.4%	266	0.26
Total					**0.34**

Note:

- For pipeline: assumed shares of power generation are divided as following: turbine 55%, current NG engine 33%, and 12% future NG engine (CA-GREET defaults)
- For HDD Truck: assumed energy consumption at 25,690 Btu/mile, average speed 5 mph, and 25 tons capacity load of CARBOB.
  for delivery to a blending station after taking consideration of 80% and 99.4% mode shares of pipeline

Table 4.06 provides details for all GHG emissions for CARBOB transport and distribution. This includes CH_4, N_2O, VOC combined with CO_2.

Table 4.06. Details of GHG from CARBOB Transportation and Distribution

	g-CO_2e/mmBtu		g-CO_2e/MJ		Total (gCO2e/MJ)
	Transp.	**Distr.**	**Transp.**	**Distr.**	
CO_2	88	266	0.08	0.26	0.34
CH_4	3.199	8.176	<0.01	<0.01	<0.01
N_2O	0.573	1.955	<0.01	<0.01	<0.01
CO	0.204	0.803	<0.01	<0.01	<0.01
VOC	0.084	0.352	<0.01	<0.01	<0.01
Total GHG	**92.9**	**277.4**	**0.09**	**0.27**	**0.36**

Section 5. CARBON EMISSIONS FROM CARBOB COMBUSTION

5.1 Combustion Emissions from Fuel

GHG emissions from the fuel occur during vehicle operation. The engine burns fuel which primarily forms CO_2. A small fraction of the fuel is emitted as CO, hydrocarbons, methane, or particulate matter. Since CO and hydrocarbon emissions are converted to CO_2 in the atmosphere within a few days, the carbon emissions are treated as CO_2. However, for the CARBOB pathway, since it is not legal in California to be dispensed as a fuel, only CO_2 emissions from carbon in fuel calculations are provided for this pathway. CA-GREET uses the carbon content in the fuel to calculate GHG emissions. In the CA-GREET model, these fuel CO_2 emissions are shown in a per mile basis and are embedded in the tank to wheel calculations. The calculations below show the CO_2 emissions per mmBtu and MJ of fuel. The carbon in fuel is calculated from the carbon content in the fuel and fuel density. Table 5.01 provides input values and sources of these values used in calculating carbon emissions from fuel. The average carbon ratio in CARBOB is 85.9% (by weight) which translates to about 76,921 grams of CO_2 per mmBtu of fuel (or **72.91** g CO_2/MJ).

Table 5.01. Inputs and Assumptions used for Calculating Combustion GHG Emissions

Description	Value	Reference
Lower Heating Value of CARBOB	113, 300 Btu/gal	AB 1007 value
Density of CARBOB	2,767 g/gal	AB 1007 value
Molecular weight of CO_2	44 g/mole	
Atomic weight of C	12 g/mole	
C factor	12/44 = 0.27	
Carbon ratio in CARBOB	85.9 % (by weight)	CA-GREET default
MJ to mmBtu conversion	1,055	
Fossil carbon in gasoline: 2,767*85.9%*44/12/113,300*10^6 = 76,219 g CO_2/mmBtu = **72.91** g CO_2/MJ CO_2 from fuel = Density * carbon ratio in gasoline/(C factor * LHV)		

APPENDIX B

CARBOB Pathway Input Values

Scenario: Average Crude Oil to California refineries to make CARBOB

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.1	
CO		1.6	
Crude Recovery			
Efficiency		92.7%	
Process Shares			
Crude		0.6%	
Residual Oil		0.6%	
Conventional Diesel		8.6%	
Pet. Coke		0.4%	
Conventional Gasoline		1.1%	
Natural Gas		72.1%	
Electricity		16.5%	
Feed Loss crude recovery		0.1%	
Equipment Shares			These are CA-GREET Defaults
Commercial Boiler - Diesel		25%	The Emission factor for CO2 is misleading as it subtracts out the methane and CO and VOC
CO_2 Emission Factor	gCO_2/mmBtu	78,167	
Stationary Reciprocating Eng. - Diesel		50%	
CO_2 Emission Factor	gCO_2/mmBtu	77,349	
Turbine - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,179	
Stationary Reciprocating Eng. - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	56,551	
Small Industrial Boiler - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	58,176	
Transportation to CA refineries			
Pipeline shares		42%	by pipeline to CA
Pipeline distance	miles	150	One way
Pipeline Energy Intensity	Btu/mile-ton	253	
Transportation to US refineries			
Pipeline distance	miles	266	One way
Pipeline Energy Intensity	Btu/mile-ton	253	
Ocean Tanker distance traveled	miles	3,550	One way
Ocean Tanker Energy Intensity	Btu/mile-ton	27	24 Btu/mile-ton for return trip
Loss Factor in Crude T&D		1.000062	
CARBOB Refining			
Efficiency		84.5%	CARBOB Refining for year 2010 - user input
Process Shares			
Residual Oil		3%	
Natural Gas		30%	
Pet. Coke		13%	
Electricity		4%	
Still Gas		50%	
Equipment shares			
Large Turbine - Natural Gas		25%	Same comment
CO_2 Emission Factor	gCO_2/mmBtu	58,179	

Parameters	Units	Values	Note
Large Industrial Boiler - Natural Gas		60%	
CO_2 Emission Factor	gCO_2/mmBtu	58,198	
Small Industrial Boiler - Natural Gas		15%	
CO_2 Emission Factor	gCO_2/mmBtu	58,176	
Industrial Boiler - Residual Oil		100%	
CO_2 Emission Factor	gCO_2/mmBtu	85,045	
Transportation			
Transportation by pipeline		80%	20% directly from refinery terminal rack
Distance	miles	50	
Energy Intensity	Btu/ton-mile	253	
Transportation by truck		20%	
Distance	miles	50	
Energy Intensity	Btu/ton-mile	1028	
Distribution by truck		99.4%	0.6% directly supplied by pipeline
Distance	miles	50	
Energy Intensity	Btu/ton-mile	1,028	
Loss Factor in CARBOB T&D		1.000201	
Fuels Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	
Residual Oil	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,686	2,651	NG Liquids
Ethanol	76,330	2,988	
Still Gas	128,590		
Transportation Mode			
Ocean Tanker	tons	250,000	Crude Oil. This is a change, the others are not
	tons	150,000	Gasoline
Heavy Duty Truck	tons	25	Crude Oil
	tons	25	Gasoline

[1] GREET Model: Argonne National Laboratory: http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
[2] California Assembly Bill AB 1007 Study: http://www.energy.ca.gov/ab1007
[3] RFG is actually blended with 10% ethanol (by volume, nominal). Ethanol free RFG is potentially also a fuel, but the fuel cycle energy inputs would differ somewhat from CARBOB. In CA, CARBOB by itself can not be used as a motor vehicle fuel but needs to be blended with an oxygenate before use.
[4] CA-GREET Model (modified by Lifecycle Associates) released February 2009 (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm)
[5] California Energy Commission – Energy Almanac http://www.energyalmanac.ca.gov/petroleum/statistics/crude_oil_receipts.html
[6] Division of Oil, Gas & Geothermal Resources, http://www.conservation.ca.gov/dog/Pages/Index.aspx.
[7] Intergovernmental Panel on Climate Change a scientific intergovernmental body tasked to evaluate the risk of climate change caused by human activity established by United Nations in 1988.
"*IPCC Technical Report 2007*" – Table TS-2 – page 33 (http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf)
[8] The sea shipping line website: http://www.seashipping.com/tools.htm
[9] Refinery Energy Efficiency Allocation Analysis based on: Wang, M., et al. (2004) *"Allocation of Energy Use in Petroleum Refineries to Petroleum Products Implications for Life-Cycle Energy Use and Emission Inventory of Petroleum Transportation Fuels"*. LCA Case Studies.